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Thermal Uniformity of Liquid Helium in Electron Bubble Chamber

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A cryogenic research apparatus to measure the movement of electrons under a high electric field in a liquid helium bath was designed and built at the Brookhaven National Laboratory and the Nevis Laboratory of Columbia University. The liquid helium chamber is a double-walled cylindrical container equipped with five optics windows and ten high voltage cables. To shield the liquid helium chamber against the external heat loads and to provide the thermal uniformity in the liquid helium chamber, the double-walled jacket was cooled by a pumped helium bath. The helium chamber was built into a commercial LN2/LHe cryostat. This paper presents the design and the numerical simulation analysis on thermal uniformity of the electron bubble chamber.

INTRODUCTION

A cryogenic research apparatus, the Electron Bubble Chamber (EBC), was designed and built at the Brookhaven National Laboratory and the Nevis Laboratory of Columbia University. The set-up is to study a new detector, using cryogenic liquids, such as liquid helium, as the detecting medium, which could provide a compact and efficient solution for a next generation neutrino detector. The EBC is used to measure the movement of electrons in a liquid helium bath under an electric field of ten kilovolt. The EBC is a double-walled cylindrical container that can stand a maximum internal pressure of 10 bar. The chamber is equipped with five optic windows and ten HV cables. Both the thermal radiation and conductive heat loads to the chamber could create serious fluid convections within the liquid helium bath, which may accelerate or decelerate the directive movement of the electrons. Since the speed of the electrons moving in the liquid helium bath is about 20 cm/s, the convective fluid flow may influence the movement of the electrons. In order to provide a static helium bath, the temperature differential in the bath must be reduced to minimum. To intercept the heat flux to the chamber, vapor cooling was provided within the double-walled jacket and in the cooling coils at top and bottom of the chamber. A commercial LN2/LHe cryostat equipped with a 80 K and a 5 K shields and a needle valve for vapor cooling was used for the experiment.

EXPERIMENTAL APPARATUS

The experimental set-up consists of a LHe/LN2 cryostat and the electron bubble chamber. The cryostat provides a low temperature test environment at about 4.2 K and has also the possibility to regulate the temperature of the EBC between 4.2 K and 3 K using a pumped helium chamber. Figure 1 shows the apparatus.

LHe/LN2 Cryostat

The LHe/LN2 cryostat consists of the vacuum chamber, the liquid nitrogen reservoir, the liquid helium reservoir, the needle valve at bottom of LHe reservoir, the vapor pumping pipes, and the top flange with all instrumentation ports. The cryostat is designed according to the overall dimensions of the EBC and the experiment operational requirement of the experiment. The height of the cryostat is 1950 mm and the diameter is 406 mm. The LHe volume is 45 liters and the minimum time interval between LHe refills is about 3 days. The bottom section of the cryostat has a removable tail that contains LN2 and LHe radiation shields surrounding the test chamber. The cryostat tail is equipped with optic windows on the sides and of the bottom of the vacuum chamber and on each radiation shield. All the windows are aligned to offer an optical access to the test cell. The windows on the cryostat and heat shields are made of Infrasil fused quartz and are designed to be easily replaceable.

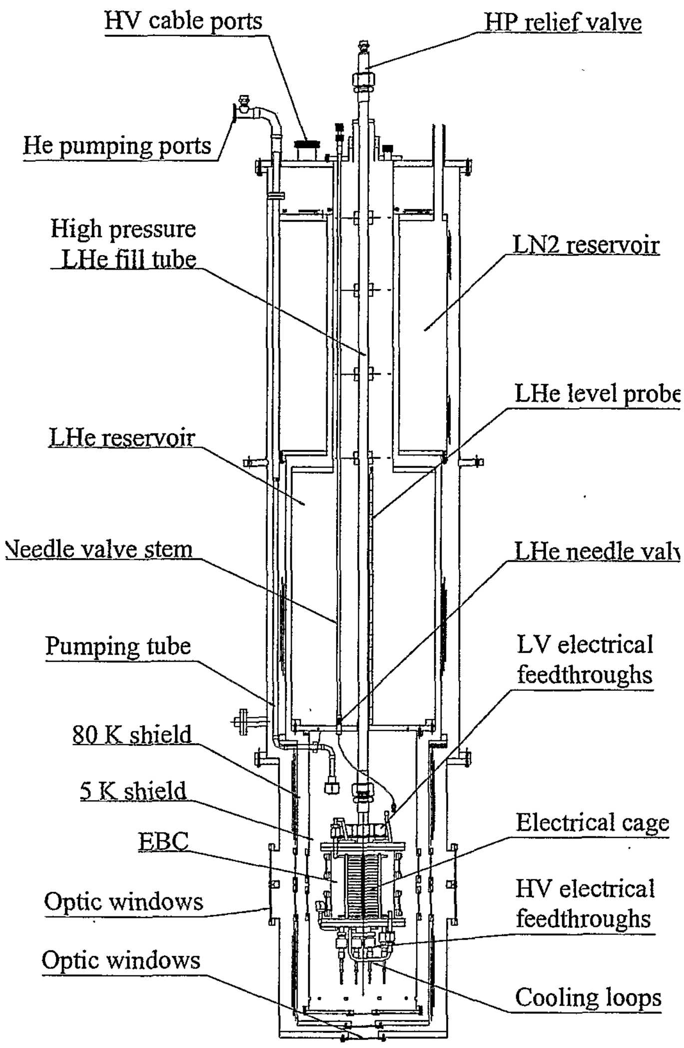

Figure 1 Electron bubble chamber cryostat

Electron Bubble Chamber

Figure 2 shows a photo of the Electron Bubble Chamber. The EBC is a cylindrical shaped double-walled LHe vessel containing 1.5 liter of liquid helium in its inner space. It has a diameter of 178 mm and a height of 194 mm. The gap within the double wall is 6.5 mm, which creates an annular space for low-pressure helium. Two copper cooling loops on the top and bottom flange are connected to the annular space. Two pumping tubes from the top flange to EBC are used to pump the vapor cooling loops in the cryostat. The helium flow from the LHe main reservoir to the vapor cooling circuit is controlled by the needle valve at the bottom of the reservoir. The pumping rate is regulated such that the vapor temperature in the annular space of the EBC ranges between 3 K and 4.2 K. The EBC was designed to be able to stand a maximum internal pressure of 10 bar. The LHe bath in the inner space is isolated from the main LHe reservoir. A high-pressure central tube passing through the LHe reservoir is used for the EBC LHe refill.

Five Sapphire windows of 25 mm diameter are mounted on the EBC; four are on the opposite sides in pair and one at the bottom. A Teflon frame cage with electrical poles providing the high electric field used as driving potential for the electrons (see Figure 3) has been placed within the EBC. The ten feedthroughs with high voltage cables coming from the top flange are located at the bottom of the EBC. The HV cables are each capable of carrying 10 kV with low current. The conducting wire is made of stainless steel and has a diameter of 1.0 mm. They are electrically insulated by a 3 mm Teflon coating sleeve of 3 mm in diameter. The HV feedthroughs have special designed dismountable cryogenic fittings for easy replacement in case of crack created in its ceramic insulation jacket during thermal cycles. To reduce the conductive heat load, the HV cables are thermally anchored along the 77 K shield and along the 4.2 K shield. There are four low voltage feedthroughs attached to the top flange of the EBC. The low voltage wires are also thermally anchored around the thermal shields to intercept the heat to the EBC. With the current design, the cooling of the BEC can be arranged in several options. One is to cool each flange individually, at top or bottom, the other is to cool the double-walled jacket only, and the third is any combination of these three coolings. To keep the temperature at the top portion of the bath higher than the bottom of the bath, an electrical heater was also installed on the top flange for heating purpose in case needed.

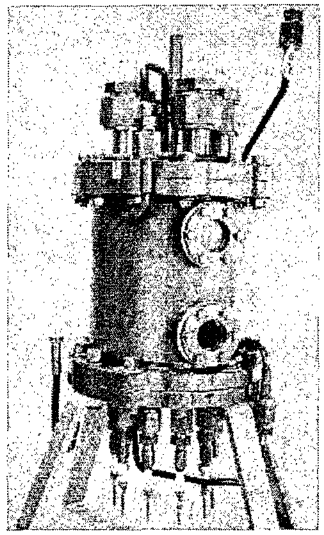

Figure 2 Photo of electron bubble chamber

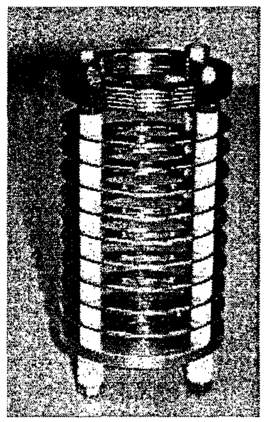

Figure 3 High voltage pole cage

Thermal Fluid Characteristics

The moving speed of the electrons under the field of the 10 kV in the liquid helium bath is estimated as 20 cm/s. The fluid convections within the liquid helium bath due to the differential temperature in the bath will carry the electrons and accelerate or decelerate their directive movement. Even more serious, is the eventual formation of gas bubbles will collect the electrons and effect their movement. To ensure a thermally uniform liquid helium bath for the electron tracking, the fluid convection must be reduced to the minimum. Three major heating sources exist to the EBC, the thermal radiation through the five windows, the conductive heat flux through the 10 HV cables, and the thermal radiation from the inner thermal shield. In order to reduce the temperature at the boundaries of the LHe bath, the LHe bath present in the double-walled jacket is pumped. By reducing the pressure in the annular space, the temperature of helium in the annular space will drop to a temperature lower than 4.2 K. The low temperature jacket will remove the heat loads from the HV cables as well as thermal radiation from the surroundings. To control the temperature in the cooling circuit, the pumping speed and the opening of the needle valve supplying LHe to the annular space need to be adjusted.

NUMERICAL SIMULATION

Computational fluid dynamic analyses were carried out to evaluate the scale of the thermal convection in the LHe bath of the EBC. The analysis were made using the commercial CFD package of Fluent, Inc.

Numerical Model

The simplified physical model for the LHe bath is shown in Figure 4. The ten small round faces at the bottom of the liquid helium boundary represent hot spots simulating the hot surfaces of the HV cables. The ten solid circle grids inside the LHe domain simulate the electrical pole cage in the bath. The mathematical model of buoyancy-driven flow was applied. The steady state, three-dimensional turbulent natural convection in the domain caused by the hot spots at the bottom as well as the flanges were modeled. The standard k-ε momentum equation and standard wall functions with full buoyancy effects were adopted for the simulation. Variable properties of liquid helium, such as density, viscosity, heat capacity, thermal conductivity, are also considered. The second-order scheme is applied for the discretization of momentum and energy.

Results and Analyses

The typical calculation results are given in Figure 5, 6, and 7. Figure 5 shows a contour pattern of the temperature field in LHe bath. Figure 6 and 7 show the vertical velocity distribution of the fluid in the radial direction inside the LHe domain without and with the grid cage, respectively. In Figure 6, the boundary temperatures at the top and lateral of the LHe domain are set at 4.0 K, and the ones at the bottom and at the hot spots are set at 4.2 K. In the case shown in Figure 7, the temperature at the top and lateral of the LHe domain is set at 3.8 K, the one at bottom at 4.0 K, and the ones at the hot spots are at 4.2 K. In these two figures, the sharpest line represents the Z-velocity of fluid close to the bottom of the LHe domain, the sharper one is taken in the vertical middle of the domain, and the smooth one is at close section to the top of the domain. The maximum Z-velocity of fluid in Figure 6 is 2.5 cm/s, which happens at the center of the LHe domain. In Figure 7, because of one layer blind grids at the bottom and at the top of the cage, the maximum Z-velocity of fluid is lower than 1.5 cm/s, and it only happens at the near wall region. The Z-velocity at the center is lower than 0.2 cm/s. These results enlightened the idea to add a skirt barrier under the bottom grid to block the fluid convection towards the central region and still allow the optic pass through the bottom window in case needed. With the help of the fluid dynamics analyzing program this idea was proven to be valid.

CONCLUSIONS

In order to measure the electron speed in a liquid helium bath under a high electric field, a small size electron bubble chamber was developed at low cost. To ensure thermal stability and nearly zero convection in the liquid helium in the tracking field, low-pressure helium vapor cooling through a double-walled chamber was applied. The numerical simulation made for this set-up indicated that the scale of the fluid convection under a temperature differential of 200 ~ 400 mK is about ten times smaller than the electron speed estimated as 20 cm/s. A kind of convection flow barrier should be used to ensure a low or zero convection regions for the electron tracking. Further analyses and tests will be performed.

ACKNOWLEDGMENTS

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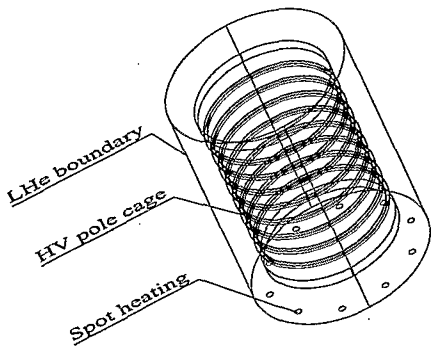

Figure 4 Liquid helium domain with hot spots and solid circle grids

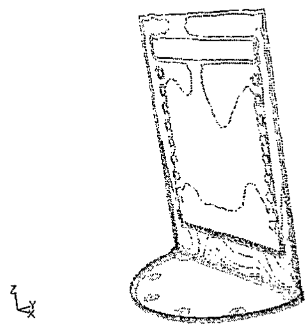

Figure 5 Typical temperature contours in EBC

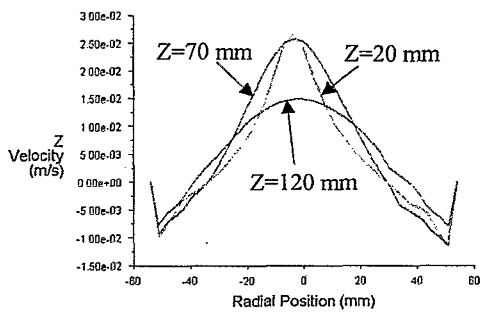

Figure 6 Vertical velocity of fluid inside LHe domain without grids

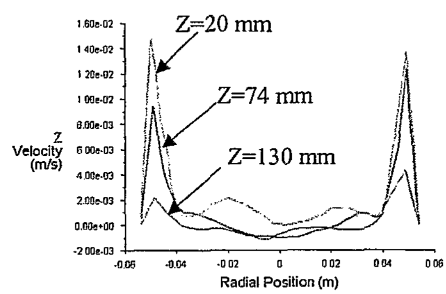

Figure 7 Vertical velocity of fluid inside LHe domain with grids